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Original Citation:

Trace element constraints on the evolution and genesis of the Monte Pulchiana Leucogranites, northern Sardinia, Italy / S. TOMMASINI; G. POLI; C. GHEZZO. - In: PERIODICO DI MINERALOGIA. - ISSN 0369-8963. - STAMPA. - 68:(1999), pp. 53-67.

Availability:

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Trace element inferences on the evolution and genesis of the Monte Pulchiana leucogranites, northern Sardinia, Italy

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Submitted January 1999 - Accepted March 1999

ABSTRACT. — The Monte Pulchiana leucogranites belong to the Sardinia-Corsica batholith and were emplaced during the post-collisional phase of the Hercynian orogeny. They consist of multiple coalescent intrusions cut by numerous aplitic dikes and outcrop along a surface of about 40 km². At least two different parental magmas have been distinguished on the basis of their geochemical characteristics. The evolution of the main group of the Monte Pulchiana leucogranites (MGL) can be accounted for by crystal fractionation process of two extreme mineral assemblages. The discrimination between evolutive and genetic processes allows to set constraints on the geochemistry of the source(s) of the Monte Pulchiana leucogranites. Geochemical and physical arguments provide evidence for a heterogeneous, andesitic-like composition source for the Monte Pulchiana leucogranites. The origin of this andesitic crust could be found in the magmatic activity which took place in the Sardinia and Corsica islands in the Ordovician, prior to the onset of the Hercynian orogeny. The source heterogeneities could have developed because of either intrinsic or extrinsic processes. The former concern differentiation of the andesitic magmas, whereas the latter

concern the percolation of the huge amount of the late-tectonic monzogranitic melts *en route* to the surface, throughout the upper portion of the andesitic crust. This resulted in the formation of a mixed, net-veined crustal source which subsequently experienced a partial melting process during the adiabatic upwelling of the Sardinia-Corsica basement occurred in the post-collisional phase of the Hercynian orogeny.

RIASSUNTO. — I leucograniti del Monte Pulchiana appartengono al Batolite Sardo-Corso e sono stati messi in posto durante la fase post-collisionale dell'Orogenesi Ercinica. Affiorano su una superficie di circa 40 km² e consistono di intrusioni multiple coalescenti tagliate da numerosi dicchi aplitici. Sulla base delle loro caratteristiche geochimiche, sono stati distinti almeno due differenti magmi parentali. L'evoluzione del gruppo principale dei leucograniti del Monte Pulchiana (MGL) può essere spiegata tramite processi di cristallizzazione frazionata di due distinte associazioni mineralogiche. La discriminazione tra i processi evolutivi e genetici ha permesso di definire i limiti della variabilità geochimica della(e) sorgente(i) di tali leucograniti. Per gli stessi, tramite argomentazioni geochimiche e fisiche, è stato possibile riconoscere una composizione eterogenea della sorgente di tipo andesitico. Tale crosta

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andesitica potrebbe derivare dall'attività magmatica sviluppata in Sardegna e Corsica nell'Ordoviciano in tempi precedenti all'Orogenesi Ercinica. Le eterogeneità della sorgente sarebbero imputabili a sia processi differenziativi che hanno interessato i magmi andesitici, che a percolazione di notevoli quantità di fusi monzogranitici tardo-tettonici che hanno attraversato le porzioni superiori della crosta andesitica durante la loro migrazione verso la superficie. Tali processi avrebbero portato alla formazione di una sorgente crostale *net-veined* che avrebbe fuso parzialmente durante la risalita adiabatica del basamento Sardo-Corso avvenuta nella fase post-collisionale dell'Orogenesi Ercinica.

KEY WORD: *Sardinia, Corsica batholith, Monte Pulchiana, Petrologia, Geochimica, crustal evolution*

INTRODUCTION

The Sardinia-Corsica batholith was structured during the Hercynian orogeny. A huge amount of granitic plutons were emplaced in three main phases of magmatic activity: syn-late-, and post-tectonic. These phases occurred during the post-collisional stage of the Hercynian orogeny and are referred to emplacement conditions varying from forced to permissive (e.g. Bralía *et al.*, 1982; Ghezzo and Orsini, 1982; Carmignani *et al.*, 1986). All intrusive rocks form a characteristic calc-alkaline suite, consisting mainly of Hlo and subordinate Cci granites, according to the classification scheme by Barbarin (1990).

The syn- and late-tectonic granites form ca. 75% of the outcrop surface of the batholith and consist of microgranular mafic enclave-bearing metaluminous tonalites and monzogranites (ca. 70%) with minor amounts of peraluminous granodiorites and monzogranites (e.g. Macera *et al.*, 1989; Di Vincenzo *et al.*, 1996). Sporadic gabbroic complexes (<5%) outcrop along the batholith and their emplacement is coeval with that of the acid intrusives of the first two phases (e.g. Tommasini and Poli

1992; Tommasini, 1993). The post-tectonic granites form the remaining of the outcrop surface of the batholith and consist of compositionally homogeneous, metaluminous leucogranites.

Most geochemical studies dealing with the batholith petrogenesis have taken into account the plutons related to the syn- and late-tectonic phases because of the interest in addressing the issue of the role of interaction processes between crustal and subcrustal magmas in the genesis of the Sardinia-Corsica batholith (e.g. Bralía *et al.*, 1982; Orsini, 1980; Cocherie, 1984; Poli *et al.*, 1989; Poli and Tommasini, 1991; Tommasini and Poli, 1992; Tommasini *et al.*, 1995). In contrast, post-tectonic leucogranites have received scarce attention on petrogenetic basis. Their genesis has been referred to adiabatic partial melting processes occurring in middle and lower crustal levels during the isostatic re-adjustment of the Hercynian belt after the collisional event (Guasparri *et al.*, 1984; Carmignani *et al.*, 1986; Poli *et al.*, 1989). The crustal source of the leucogranites has been referred to i) the same as that of the late-tectonic granites which underwent lower degrees of partial melting (Poli *et al.*, 1989); ii) a residual crust which experienced a previous partial melting process related to the genesis of the late-tectonic granites (Guasparri *et al.*, 1984).

This controversy may be due in part, to the fact that the genesis of leucogranites has been considered in general terms by Guasparri *et al.* (1984) and Poli *et al.* (1989), without discriminating between evolutive and genetic processes. The aim of the present paper is to quantitatively explain differentiation processes occurring in post-tectonic leucogranites outcropping in a limited area of Northern Sardinia (Monte Pulchiana) in order to discriminate between evolutive and genetic processes and to set constraints on the geochemistry of the source of leucogranites in the Sardinia-Corsica batholith.

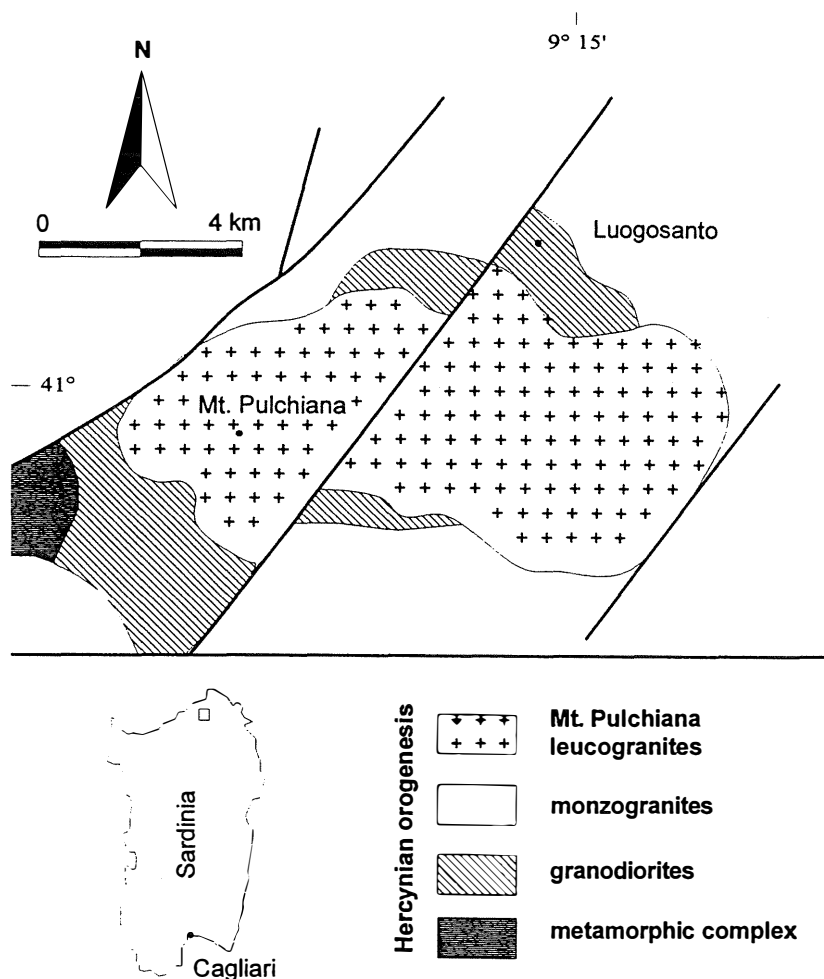


Fig. 1. – Geological sketch map of the Monte Pulchiana area after Frezzotti *et al.* (1988).

GEOLOGY AND PETROGRAPHY

The Monte Pulchiana leucogranites as well as all post-tectonic leucogranitic intrusions of the Sardinia-Corsica batholith share the following peculiar characteristics (Ghezzi *et al.*, 1979, 1981; Ghezzi and Orsini, 1982; Guasparri *et al.*, 1984): i) shallow crustal levels of emplacement (2-4 km) and permissive character; ii) narrow compositional range (leucogranites); iii) water undersaturated

character and high temperature (ca. 800 °C) of magmas; iv) absence of mafic microgranular enclaves which are ubiquitous in the syn- and late-tectonic intrusions; v) association with Mo, porphyry-like mineralisations.

The Monte Pulchiana leucogranites are located north of Tempio Pausania, in Northern Sardinia (fig. 1). The outcropping surface is about 40 km², and they consist of multiple coalescent intrusions cut by numerous aplo-pegmatitic dikes. No radiometric data are

available on these leucogranites. Mesoscale structural relationships indicate an emplacement successive to the surrounding late-tectonic plutons, during the post-tectonic phase of the Hercynian orogeny in the Sardinia-Corsica batholith (e.g. Ghezzo and Orsini, 1982; Guasparri *et al.*, 1984; Carmignani *et al.*, 1986).

The Monte Pulchiana leucogranites are coarse- to medium-grained equigranular rocks and have hypidiomorphic textures. The main mineralogical phases are quartz, K-feldspar, plagioclase, and biotite.

Quartz is the dominant phase (35-40 vol.%) and occurs as anhedral grains, sometimes displaying undulatory extinction. K-feldspar is always strongly perthitic and occurs as subhedral and anhedral grains. The latter grains can be poikilitic on plagioclase and biotite. K-feldspar is mainly orthoclase, frequently Carlsbad-twinned, although microcline with the characteristic tartan-twinning occurs in subordinate amounts. Plagioclase occurs as tabular, zoned grains. The core displays euhedral shapes, even though sponge-like textures are also present, and is often sericitised; the rim is anhedral. Microscope estimations yield rather uniform compositions: oligoclasic cores and almost pure albitic rims. Iron-rich biotite occurs as subhedral grains and shows a dark brown-brownish-green pleochroism. Clots of biotite are present in some samples (N120 and N121). Biotite is the only mafic phase occurring in the leucogranites, and its modal content is < 5 vol.%. No primary muscovite is present in the samples.

Accessory phases consist of magnetite, apatite, zircon and allanite, and are often hosted in biotite grains. Secondary phases are epidote and chlorite from biotite alteration, and sericite from feldspars alteration.

GEOCHEMISTRY

Major and trace element analyses are reported in Table 1 for representative samples

of the Monte Pulchiana leucogranites (enclosed is also one aplite). Particular care has been paid in the selection of fresh samples exhibiting no pervasive alteration. Major elements have been determined by X-ray fluorescence spectrometry (XRF) with full matrix correction after Franzini and Leoni (1972), except MgO and Na₂O which have been determined by atomic absorption analysis, and FeO by titration. V, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, and Pb have been determined by XRF after Kaye (1965); other trace elements by neutron activation analysis after Poli *et al.* (1977). The precision is better than 15% for V, Cu, Ga, Nb, Ba, Pb, Tb, and Lu, better than 10% for Ni, Y, Zr, Ta, and Yb, and better than 5% for all the other elements. The accuracy has been tested on international standards and is better than 10%.

The Monte Pulchiana Leucogranites have a calc-alkaline, I-type affinity (Table 1): total alkali content is about 8 wt%, mean ASI value and normative corundum are 1.09 ± 2 and 1.07 ± 20 , respectively, no Al-silicate phase other than biotite occurs in the samples.

Selected variation diagrams, using both SiO₂ and CaO as differentiation indexes, are reported in fig. 2. Despite the fairly homogeneous silica content (74-76 wt.%), other major and trace elements vary significantly and suggest the occurrence of differentiation processes during the emplacement and cooling history of the leucogranites. In contrast to some elements (e.g. Sr, Al₂O₃, CaO, Ba, Zr) which define a single evolutionary trend in interelemental diagrams, most major and trace elements suggest that the sample N115 is unrelated to the Main Group of Leucogranites (MGL). The sample N115 plots off the trend defined by the MGL in the MgO, V, and Na₂O vs. SiO₂ diagrams. Moreover, in the K₂O vs. CaO diagram this sample has significantly lower K₂O content.

Chondrite-normalised REE patterns (fig. 3) display variable LREE fractionation (La/Sm 7.5-4.4) and fairly flat HREE (Tb_N/Yb_N = 0.9-1.2). LREE and La/Sm ratio exhibit a decrease

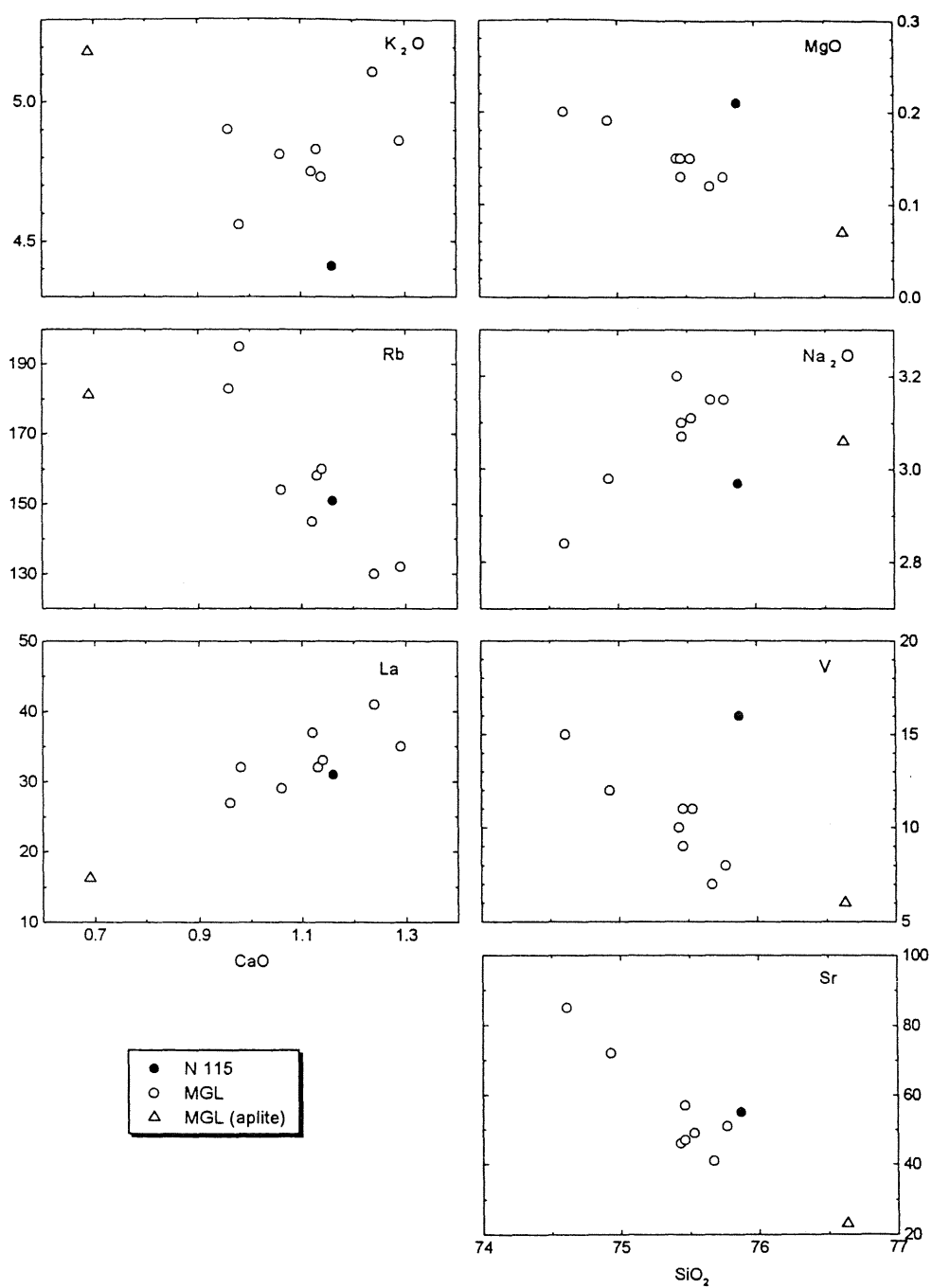


Fig. 2. – Selected Harker diagrams for the Monte Pulchiana leucogranites.

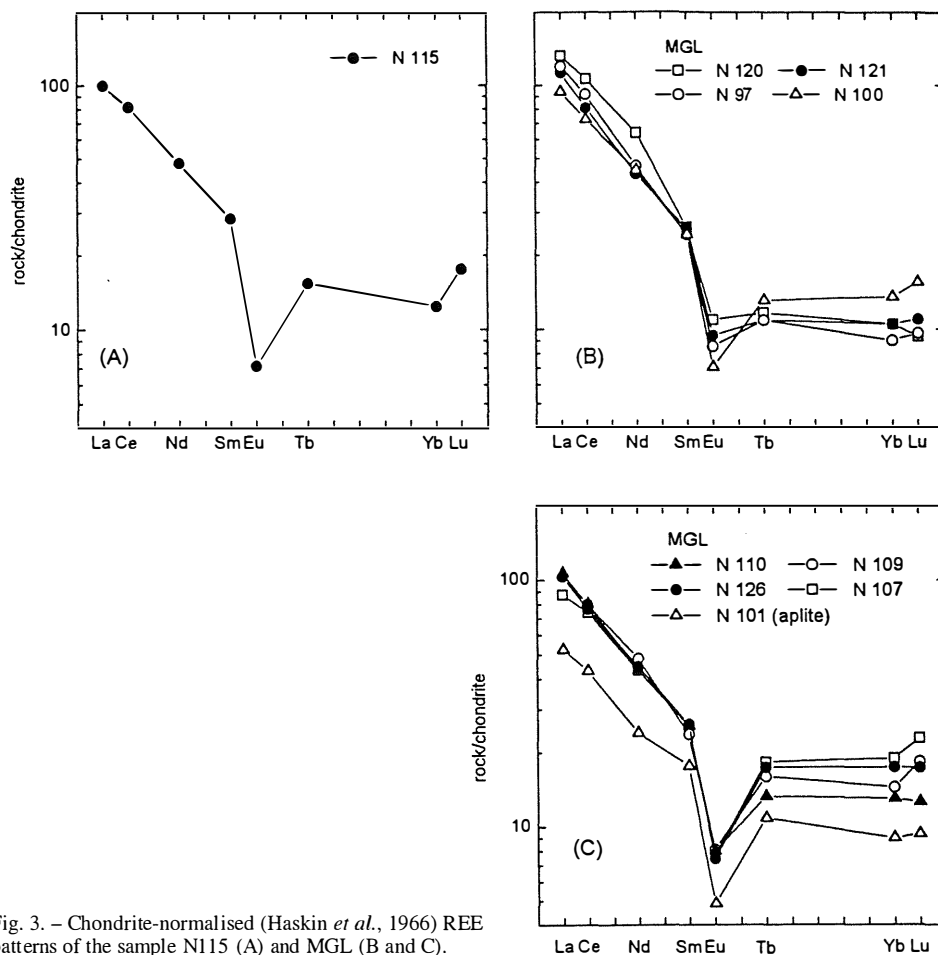


Fig. 3. – Chondrite-normalised (Haskin *et al.*, 1966) REE patterns of the sample N115 (A) and MGL (B and C).

with differentiation in the MGL. Eu negative anomaly and HREE content increase with differentiation in the MGL, except the aplite which shows a strong HREE depletion. Also, the Th_N/Yb_N ratio of the sample N115 is slightly higher than the mean value of the MGL (1.24 and 1.06, respectively).

DISCUSSION

The distinct geochemical features of sample N115 (fig. 2 and 3) clearly indicate that is

unrelated to the MGL. Moreover, its high Th content is not consistent with the differentiation of the MGL (see below). Sample N115 could, therefore, represent a different batch of magma.

The linear trends exhibited by the MGL (except the aplite) in binary diagrams (fig. 2) suggest that differentiation mechanisms responsible for their evolution could be either fractional crystallisation or partial melting processes. Geochemical constraints allow to reject the partial melting hypothesis. The positive correlation between La (and other LREE) and CaO (fig. 2) would require a

TABLE 1

Major (%) and trace element (ppm) analyses of the Monte Pulchiana leucogranites.

| Class. | MGL | | | | | | | | | |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| | N 115 | N 120 | N 121 | N 126 | N 97 | N 107 | N 109 | N 100 | N 110 | N 101 |
| | leucog | leucog | leucog | leucog | leucog | leucog | leucog | leucog | leucog | aplite |
| SiO ₂ | 75.87 | 74.61 | 74.93 | 75.43 | 75.46 | 75.46 | 75.53 | 75.67 | 75.77 | 76.63 |
| TiO ₂ | 0.24 | 0.38 | 0.34 | 0.23 | 0.24 | 0.17 | 0.20 | 0.15 | 0.19 | 0.07 |
| Al ₂ O ₃ | 12.93 | 13.31 | 13.44 | 13.23 | 13.21 | 13.38 | 13.16 | 13.25 | 13.13 | 12.94 |
| Fe ₂ O ₃ | 0.40 | 0.63 | 0.45 | 0.42 | 0.39 | 0.38 | 0.46 | 0.49 | 0.33 | 0.31 |
| FeO | 1.08 | 0.92 | 0.94 | 0.98 | 1.02 | 0.92 | 0.94 | 0.76 | 0.88 | 0.61 |
| MnO | 0.05 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| MgO | 0.21 | 0.20 | 0.19 | 0.15 | 0.15 | 0.13 | 0.15 | 0.12 | 0.13 | 0.07 |
| CaO | 1.16 | 1.24 | 1.29 | 0.98 | 1.12 | 0.96 | 1.13 | 1.06 | 1.14 | 0.69 |
| Na ₂ O | 2.97 | 2.84 | 2.98 | 3.2 | 3.07 | 3.10 | 3.11 | 3.15 | 3.15 | 3.06 |
| K ₂ O | 4.41 | 5.11 | 4.86 | 4.56 | 4.75 | 4.90 | 4.83 | 4.81 | 4.73 | 5.18 |
| P ₂ O ₅ | 0.04 | 0.05 | 0.05 | 0.03 | 0.03 | 0.03 | 0.04 | 0.03 | 0.02 | 0.02 |
| LOI | 0.63 | 0.66 | 0.48 | 0.72 | 0.50 | 0.52 | 0.40 | 0.46 | 0.47 | 0.39 |
| ASI | 1.11 | 1.08 | 1.09 | 1.11 | 1.09 | 1.11 | 1.07 | 1.08 | 1.07 | 1.09 |
| Cor | 1.26 | 0.97 | 1.05 | 1.32 | 1.05 | 1.31 | 0.86 | 1.01 | 0.81 | 1.09 |
| Sc | 4.6 | 3.9 | 4.5 | 4.5 | 4.2 | 4.5 | 4.2 | 4.4 | 3.9 | 2.9 |
| V | 16 | 15 | 12 | 10 | 11 | 9 | 11 | 7 | 8 | 6 |
| Co | 2.7 | 2.0 | 2.4 | 2.3 | 2.2 | 1.9 | 1.7 | 1.2 | 1.9 | 1.2 |
| Ni | 5 | 5 | 7 | 4 | 5 | 4 | 9 | 7 | 8 | 6 |
| Cu | 4 | 4 | 3 | 4 | 4 | 3 | 1 | 3 | 2 | 4 |
| Zn | 36 | 30 | 29 | 37 | 36 | 36 | 38 | 35 | 34 | 24 |
| Ga | 24 | 22 | 26 | 28 | 24 | 29 | 26 | 27 | 27 | 27 |
| Rb | 151 | 130 | 132 | 195 | 145 | 183 | 158 | 154 | 160 | 181 |
| Sr | 55 | 85 | 72 | 46 | 57 | 47 | 49 | 41 | 51 | 23 |
| Y | 24 | 18 | 23 | 33 | 16 | 37 | 28 | 29 | 24 | 18 |
| Zr | 103 | 107 | 98 | 101 | 99 | 96 | 115 | 99 | 93 | 34 |
| Nb | 8 | 4 | 15 | 9 | 4 | 12 | 9 | 7 | 15 | 9 |
| Ba | 305 | 634 | 502 | 448 | 460 | 432 | 457 | 338 | 483 | 105 |
| Hf | 3.6 | 3.6 | 3.6 | 3.5 | 3.6 | 4.6 | 4.3 | 4.2 | 3.7 | 1.2 |
| Ta | 0.94 | 0.49 | 0.85 | 1.58 | 0.83 | 1.49 | 1.20 | 0.82 | 1.21 | 0.82 |
| Pb | 25 | 23 | 27 | 29 | 25 | 30 | 27 | 28 | 28 | 28 |
| Th | 33 | 18.2 | 15.8 | 22 | 16.8 | 21 | 15.7 | 18.0 | 18.2 | 12.0 |
| La | 31 | 41 | 35 | 32 | 37 | 27 | 32 | 29 | 33 | 16.2 |
| Ce | 69 | 89 | 68 | 64 | 77 | 62 | 67 | 61 | 67 | 36 |
| Nd | 28 | 37 | 25 | 26 | 27 | 25 | 28 | 26 | 25 | 14.0 |
| Sm | 6.0 | 5.5 | 5.4 | 5.5 | 5.1 | 5.4 | 5.0 | 5.1 | 5.4 | 3.7 |
| Eu | 0.53 | 0.81 | 0.70 | 0.55 | 0.63 | 0.57 | 0.60 | 0.52 | 0.59 | 0.36 |
| Tb | 0.76 | 0.57 | 0.53 | 0.85 | 0.53 | 0.89 | 0.78 | 0.64 | 0.65 | 0.53 |
| Yb | 2.5 | 2.1 | 2.1 | 3.5 | 1.8 | 3.8 | 2.9 | 2.7 | 2.6 | 1.8 |
| Lu | 0.55 | 0.29 | 0.34 | 0.54 | 0.30 | 0.71 | 0.57 | 0.48 | 0.39 | 0.29 |
| Eu/Eu* | 0.33 | 0.62 | 0.57 | 0.35 | 0.52 | 0.36 | 0.41 | 0.40 | 0.43 | 0.35 |
| (Tb/Yb) _n | 1.24 | 1.11 | 1.03 | 0.99 | 1.20 | 0.96 | 1.10 | 0.97 | 1.02 | 1.20 |
| Σ REE | 159 | 195 | 154 | 155 | 166 | 148 | 158 | 144 | 154 | 86 |

ASI: mol [Al₂O₃ (CaO+Na₂O+K₂O)] corrected for apatite content. Cor: CIPW normative corundum,

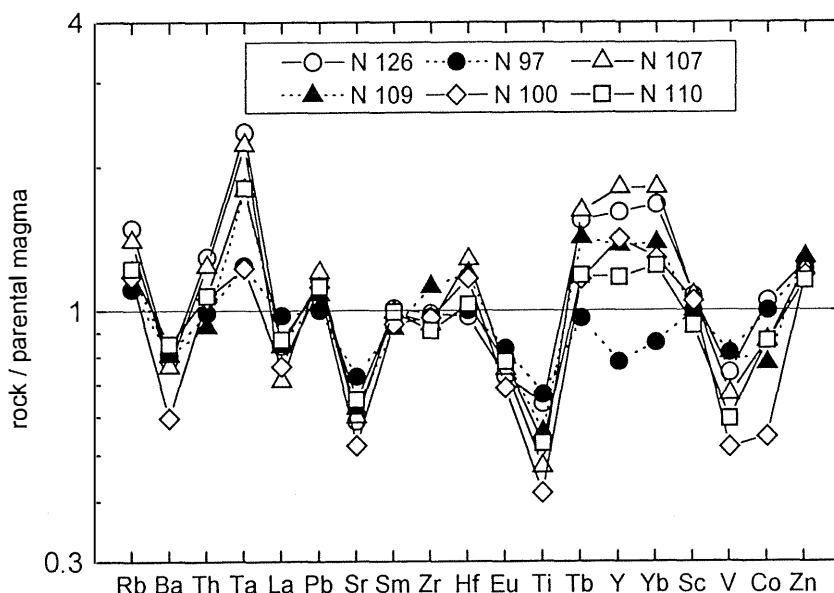


Fig. 4. – Spiderdiagram of the MGL normalised to the hypothetical parental magma. Normalisation factors are the average N120 and N121 values (see text).

compatible behaviour of LREE during partial melting, i.e. the greater the degree of partial melting the higher the content of La in the magma. This fact is in contrast with both models proposed for the genesis of leucogranites in the Sardinia-Corsica batholith, that indicate an incompatible behaviour of La (Guasparri *et al.*, 1984; Poli *et al.*, 1989). Also, the compatible behaviour of La would conservatively require a content in the source > 50 ppm, a value much too high for both an andesitic composition source (Poli *et al.*, 1989) and a residual, partially granulitised source (Guasparri *et al.*, 1984).

Several lines of geochemical evidence indicate, on the other hand, fractional crystallization as the leading mechanism responsible for the evolution of the MGL (except the aplite). In the spiderdiagram of fig. 4, elemental abundances of the evolved MGL samples are normalised to the average contents of the least evolved samples (N120 and N121), which have been considered representative of the hypothetical parental magma. The slight positive Rb spike and the negative Ba, Sr, Eu,

Ti, V, and Co spikes exhibited by the evolved MGL (fig. 4) are consistent with fractionation of feldspars and minor amounts of biotite and magnetite (e.g. see Kd values in Henderson, 1986). The strong positive Ta spike suggests no fractionation of Ta-bearing phases, at least in significant amounts as to make this element compatible. The near unity enrichment factors of Zr and Hf, together with the enrichments in Y and Yb suggest a limited fractionation of zircon. In addition, the strong enrichment in Tb rules out apatite fractionation, as this phase partitions middle REE (e.g., Henderson, 1986). The smooth negative La spike together with the decrease of the La/Sm ratio with 6 differentiation (fig. 3b and c), and the scattered enrichments/depletions of Th, suggest minor allanite fractionation.

Quantitative estimations of the MGL differentiation.

In order to quantitatively estimate the fractional crystallization process responsible for the MGL evolution, a partition coefficient

least square computation has been performed (Table 2). On the basis of the previously outlined geochemical characteristics exhibited by the MGL, the bulk distribution coefficients (D) and the liquid lines of descent have been graphically calculated for a set of trace elements using the Rayleigh fractional crystallization equation (fig. 5). The set of trace elements used in the calculation has been chosen in order to take into account the effects of the fractionation of the proposed main and accessory phases (fig. 4). Starting from the graphically determined bulk partition coefficients and using partition coefficients from the literature (Table 2), the relative proportion of minerals in each fractionating assemblage has been calculated using a least square method (e.g., Wright and Doherty, 1970).

The evolution of the MGL can be accounted for by crystal fractionation of two extreme mineral assemblages (fig. 5). In the Ba/Sr and V vs. Rb diagrams, the calculated Ds of the two liquid lines of descent are consistent with fractionation of different amounts of feldspars + biotite + magnetite (Table 2). The former (solid line) has higher amount of plagioclase +

biotite + magnetite, and lower amount of K-feldspar than the latter (dotted line). Thus the overall increase and decrease in the Ba/Sr ratios and V contents, respectively, is higher in the former liquid line of descent than the latter. The decrease and increase of the La/Th and Y/Hf ratios, respectively, suggest allanite and zircon fractionation. Zircon fractionation is also consistent with the almost constant Zr content of the MGL samples, which indicates a D^{Zr} near unity.

The aplite shows trace element ratios and abundances (Table 1) that significantly deviate from the evolutive trend of the MGL. Most of these departures could be readily explained by changes of the fractionating mineral assemblage in the final stages of crystallization, even though it cannot be quantitatively estimated the effect of a hypothetical overprinting by final stage fluids. The significant lower Ba/Sr ratio of the aplite (4.6) than MGL samples (fig. 5) can, in fact, be accounted for by a decrease and/or increase of the amount of fractionating plagioclase and/or biotite, respectively. Moreover, the decrease of Sm and HREE (fig. 3c) along with the decrease of Ta, Zr, and Hf can indicate that apatite entered the

TABLE 2

Fractional crystallisation model for the evolution of the Monte Pulchiana leucogranites.

| Element | Estimated bulk D | | Fractionating minerals (100% normalised) | | |
|-----------|------------------|------|--|-------|-------|
| | D1 | D2 | | FM1 | FM2 |
| V | 3.7 | 1.7 | Qz | 24.20 | 52.36 |
| Rb | 0.3 | 0.1 | Pl | 40.24 | 24.15 |
| Ba | 1.9 | 1.3 | Kf | 23.19 | 18.12 |
| Sr | 2.9 | 1.9 | Bi | 7.90 | 3.00 |
| Hf | 1.15 | 0.85 | Zr | 0.11 | 0.08 |
| Y | 0.25 | 0.2 | All | 0.11 | 0.09 |
| La | 1.75 | 1.3 | Magn | 4.23 | 2.20 |
| Th | 0.5 | 0.4 | | | |
| | | | SSR | 0.06 | 0.04 |

The model is for two different fractionating mineral assemblages (FM1 and FM2) at constant D. The evolution of the two liquid lines of descent is reported in fig. 5 at step of 10% of residual liquid (F). Qz: quartz; Pl: plagioclase; Kf: Kfeldspar; Bi: biotite; Zr: zircon; All: allanite; Magn: magnetite. SSR: Sum of Squares of Residuals between observed (fig. 5) and estimated D. Data on partition coefficients from Henderson (1986), Rollison (1993), Sawka (1988), Bacon and Druitt (1988), Ewart and Griffin (1994), Luhr and Carmichael (1980).

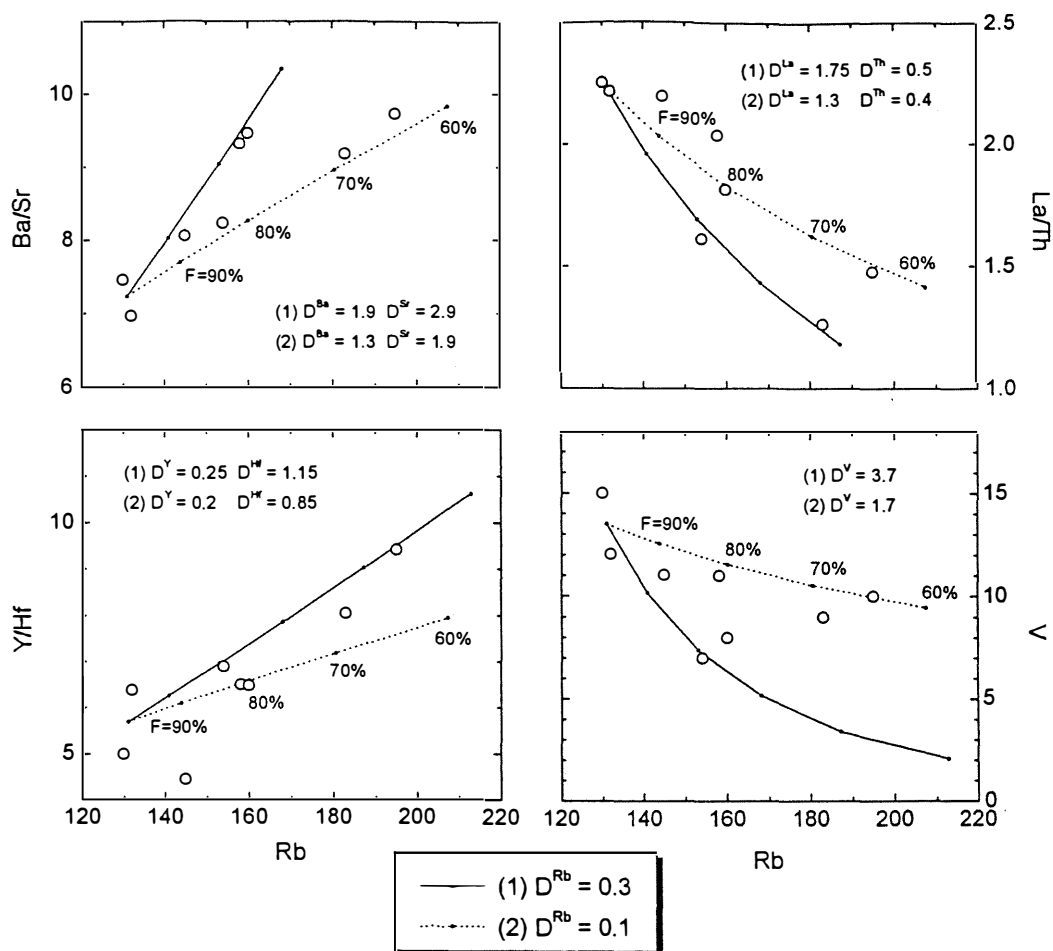


Fig. 5. – Model for the evolution of the MGL (see Table 2). The estimated bulk distribution coefficients (D) and the liquid lines of descent (at steps of 10% F) for the two extreme fractionating mineral assemblages are reported.

fractionating mineral assemblage, and the amount of fractionating zircon increased.

Geochemical interferences on the crustal sources of the two leucogranitic parental magmas.

The discrimination between evolutive and genetic processes discussed in the previous section, allows to set constraints on the geochemical characteristics of the source(s) of the Monte Pulchiana leucogranites considering

only their parental magmas. The two leucogranitic parental magmas (N120-N121 and N115) reveal significant differences in both major and trace element abundances (Table 1). The similar silica content, however, argues against the hypothesis of different degrees of partial melting of the same source to produce the two parental magmas. On the other hand, geochemical differences could be due to similar partial melting degrees of a heterogeneous source. Moreover, the $(Tb/Yb)_N$

ratios near unity (fig. 3, Table 1) indicate that either partial melting occurred above the stability field of garnet or garnet was not a residual phase after melt extraction.

Source heterogeneities concern physico-chemical as well as mineralogical differences. For example, the different CaO, Na₂O, and K₂O contents of the parental magmas (Table 1, fig. 2) could be due to either differences in H₂O or during partial melting (e.g. Holtz and Johannes, 1991) or differences in the modal mineralogy of the sources. Rb and Ba contents reveal differences of the K-feldspar/biotite ratio in the residue after the extraction of the melts: the residue of the source of sample N115 should have been enriched in K-feldspar because of the significant lower Ba and similar Rb contents than samples N120-N121. This hypothesis is also consistent with the lower Sr and Eu contents of sample N115 than N120-N121, suggesting a strong partitioning of these elements in the residue. In addition to K-feldspar, the partitioning could also be due to a greater amount of residual plagioclase.

LREE contents could be consistent with a residue having higher amounts of either main (e.g. amphibole, clinopyroxene) or accessory (e.g. apatite) phases going from samples N120-N121 to N115. However, the enrichment in LREE-buffering phases is not consistent with the highest Th content of sample N115 (Table 1). Since these phases partition LREE as well as Th (e.g. Henderson, 1986), Th content in the parental magmas argues for different abundances of Th in the sources.

Physico-chemical heterogeneities in the source regions of the two parental magmas are suggested by the overall geochemical arguments. This is not surprising given the geochemical diversity of rocks of the middle-lower crust outcropping on the Earth's surface. In order to discriminate between the two proposed sources of the post-tectonic leucogranitic magmas of the Sardinia-Corsica batholith (Guasparri *et al.*, 1984; Poli *et al.*, 1989), the trace element contents of the parental magmas of the Monte Pulchiana leucogranites have been plotted in the spiderdiagrams of fig.

6. Their trace element contents have been normalised to an andesitic crustal source (fig. 6a) and to a residual, partially granulitised crustal source (fig. 6b), according to the models by Poli *et al.*, (1989) and Guasparri *et al.*, (1984), respectively. The patterns exhibited by the two parental magmas reveal no significant differences in terms of positive and negative spikes (fig. 6), which could favour a model compared to the other. Also, the previously outlined geochemical arguments about source heterogeneities appear to apply to the andesitic as well as to the residual source. However, enrichment factors, in particular for Rb, do exhibit significant differences which favour the andesitic source model.

In the residual source model, the Rb enrichment factors (65-78) place an upper limit to the degree of partial melting equal to 1.5%, assuming a bulk distribution coefficient for Rb (D^{Rb}) equal to zero. However, extraction of very small melt fractions, though consistent with models of mantle melting, are not likely to occur in crustal environments (McKenzie, 1985). Because of the acidic character, i.e. high viscosity, small melt fractions in the crust are likely to remain in-situ and form migmatitic terrains rather than to rise up to shallow crustal levels. In addition, the $D^{Rb}=0$ argues against the presence of biotite in the residue, requiring larger amount of residual K-feldspar to keep the enrichment factor of Ba close to unity, in particular for sample N115. However, K-feldspar does partition also Rb (Henderson, 1986) and this fact makes the D^{Rb} increase and the degree of partial melting decrease. In contrast, the trace element enrichment factors in the andesitic source model are not as high as those in the residual source model (fig. 6), and are consistent with low degree of partial melting (15-25%) of the andesitic source leaving a residue composed of quartz, plagioclase, K-feldspar, amphibole, biotite, clino- and orthopyroxene, and accessory amounts of apatite, zircon, and titanite (Poli *et al.*, 1989).

Thus, geochemical as well as physical constraints favour the andesitic in contrast to

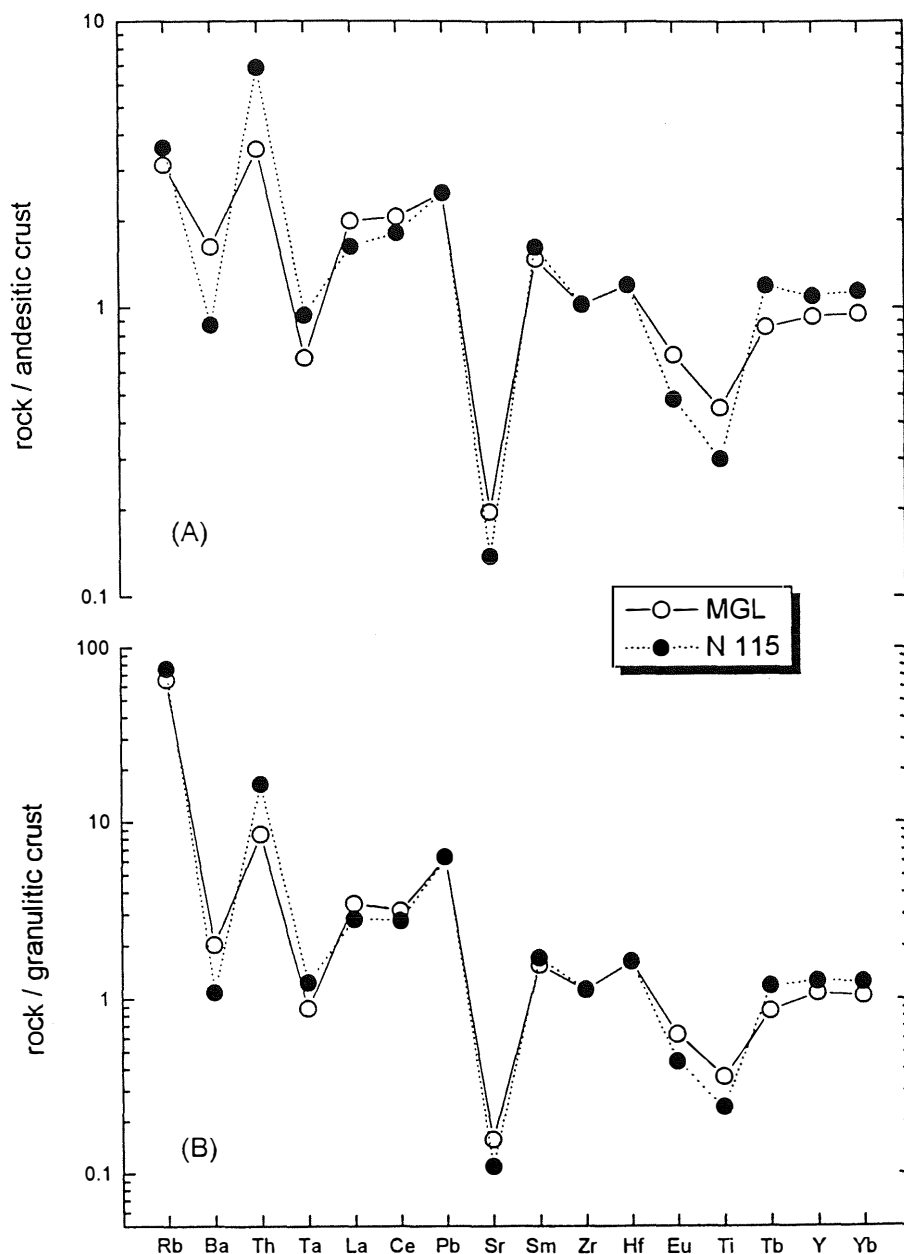


Fig. 6. – Spiderdiagrams of the two Monte Pulchiana parental magmas normalised to a hypothetical andesitic-like (A) and granulitic-like (B) source. The MGL parental magma is the average of samples N120 and N121. Composition (ppm except Ti in wt% TiO_2) of the andesitic-like source: Rb=42, Ba=350, Th=4.8, Ta=1, La=19, Ce=38, Pb=10, Sr=400, Sm=3.7, Zr=100, Hf=3, Eu=1.1, TiO_2 =0.8, Tb=0.64, Y=22, Yb=2.2. Composition (ppm except Ti in wt% TiO_2) of the granulitic-like source: Rb=2, Ba=280, Th=2, Ta=0.76, La=11, Ce=25, Pb=4, Sr=500, Sm=3.5, Zr=91, Hf=2.2, Eu=1.2, TiO_2 =1, Tb=0.64, Y=19, Yb=2. Data from Taylor and McLennan (1985), and Poli *et al.*, (1989).

the residual source, as the plausible crustal source of the post-tectonic leucogranitic magmas of the Sardinia-Corsica batholith. This is further supported by experimental petrology data on melting of crustal protoliths (fig. 7). Metasedimentary protoliths are not likely to have produced the Monte Pulchiana leucogranites, whereas igneous, intermediate composition protoliths (akin the andesitic-like source) originate melts which have major element composition similar to that of the Monte Pulchiana leucogranites (fig. 7).

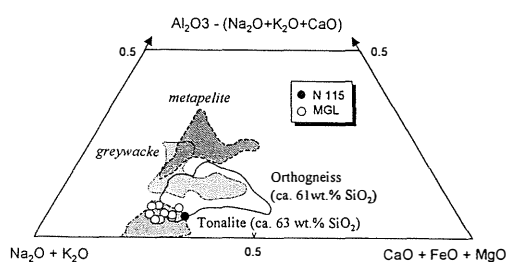


Fig. 7. – Triangular diagram $[Al_2O_3 - (Na_2O + K_2O + CaO)] - [K_2O + Na_2O] - [CaO + FeO + MgO]$ (molar) reporting the composition of experimental petrology data on melt composition from different crustal protoliths: metagreywacke, Montel and Vielzeuf (1997); metapelite, Patino Douce and Johnston (1991), biotite orthogneiss, Patino Douce and Beard (1995); tonalite, Patino Douce (1997). The Monte Pulchiana leucogranites are within the fields of igneous, intermediate composition protoliths, and provide further evidence for their origin from partial melting of an andesite-like crustal source Poli *et al.*, 1989).

The origin of this andesitic crust might be found in the calc-alkaline magmatic activity which took place in the Ordovician in the Sardinia and Corsica islands (Tommasini *et al.*, 1995). The products of this magmatic activity extensively outcrop along the Sardinia-Corsica batholith and are related to subduction, Cordillera-like geodynamic setting (Memmi *et al.*, 1982, 1983; Carmignani *et al.*, 1986). The exposed outcrops of the ordovician magmatic activity are interbedded within upper crust and volcanoclastic metasediments, and mainly consist of acidic volcanics (Porphyroids) with minor andesitic and basaltic volcanics (Memmi *et al.*, 1982, 1983; Carmignani *et al.*, 1986).

However, according to the models of crust accretion (e.g. Taylor and McLennan, 1985; Huppert and Sparks, 1988), there is no reason to reject the hypothesis of significant underplating of andesitic and basaltic magmas which supplied heat to initiating crustal anatexis and formed the lower crustal levels of the Sardinia-Corsica basement. Thus, the andesitic composition middle-lower crust developed in the Ordovician, could have been the crustal source of the Hercynian late-tectonic monzogranitic magmas as well as that of the Hercynian post-tectonic leucogranitic magmas.

The source heterogeneities, highlighted by the distinct geochemical features of the leucogranitic parental magmas of the Monte Pulchiana, demand for some explanations, even though they can just be matter of speculations. The heterogeneities of the andesitic sources could have developed because of either intrinsic or extrinsic processes. The former concern the differentiation of the andesitic magmas after underplating, whereas the latter concern the percolation and partial stagnation of the huge amount of the late-tectonic monzogranitic melts *en route* to the surface, throughout the upper portions of the andesitic source. This resulted in the formation of a mixed, net-veined crustal source which subsequently experienced a partial melting process during the adiabatic upwelling of the Sardinia-Corsica basement. occurred in the post-tectonic regime of the Hercynian orogenesis (e.g. Ghezzo and Orsini, 1982; Guasparri *et al.*, 1984; Carmignani *et al.*, 1986; Poli *et al.*, 1989). Another possibility is the overlapping of both processes in the formation of the heterogeneous crustal source. This hypothesis makes the scenario much more complicated even though it is perhaps more geologically reliable.

The outlined geochemical constraints on source heterogeneities may be useful for in progress research on the characterization of the crustal levels responsible for the genesis of the widespread post-tectonic leucogranitic magmatism occurred during the Hercynian orogenesis in the Sardinia and Corsica islands.

ACKNOWLEDGEMENTS

We are indebted to P. Manetti for comments and helpful discussions. We wish to thank D. Chiocchini and M.L. Todaro for technical assistance. We wish to express our deepest appreciation to A. Rottura and A. Caggianelli for their constructive reviews. This work was supported by M.U.R.S.T. of Italy (grants 40% and 60%).

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